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CONTROLLED ACCELERATED LIFE TESTING

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13. ABSTRACT *(Maximum 200 words)*

This report guides the reader through the step-by-step process of planning a controlled accelerated life test using combined simulated environments. The purpose is to reduce the time and cost to bring a system to the hardware maturity required to enter operational testing with reasonable confidence of success. The report states that simulation is a test-analyze-and-fix process and is not intended to result in an operational hardware reliability prediction. The report also compares the strengths and weaknesses of the natural and simulated environments and where natural environments may be more time and cost effective than the simulated ones.

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PREFACE

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CONTROLLED ACCELERATED LIFE TESTING

1. INTRODUCTION

Accelerated testing is performed for the following two purposes.

- To simulate the actual use of the environment improving the reliability of a product, but shortening the calendar time in which it is accomplished. This is the familiar test, analyze, and fix (TAAF) process with the clock accelerated to save time and costs. Several test phases may be required to bring the system to its desired maturity.

- To stimulate environments causing stresses that screen products for latent defects. This is called environmental stress screening (ESS), a manufacturing process that is performed over a relatively short period of time. Screening time is measured in minutes or hours, depending upon the screen used.

This section of the Reliability Growth Handbook concerns accelerated testing by the simulation of environments.

2. FAILURE ANALYSIS, THE KEYSTONE OF ACCELERATED TESTING

Unfortunately, companies go to considerable expense in purchasing environmental chambers or contracting for environmental test services but fail to perform a detailed failure analysis. An assumption that the environmental stresses were too intense or long in duration can be costly in the long run. One needs to know exactly what in the circuit failed, why it failed (poor manufacture, faulty design, part fatigue, material contamination, faulty fault detection equipment, etc.), and devise a process for corrective action.

Although not exactly classified as failure analysis, thermal imaging can be a powerful tool in nondestructive testing. Accelerated testing will cause deterioration of solder joints, electronic parts, and electrical-mechanical assemblies. As these parts deteriorate, the entropy of the assembly rises causing minute temperature changes at weakening points. Measuring and storing thermal images of each assembly before and after being subjected to laboratory simulated environments can provide important information concerning the deterioration of the product. Thermal images can detect temperature changes in junctions and parts down to 0.02 °C. Testing can be accelerated by finding such rising temperatures and designing methods of keeping them to a minimum.

3. ENVIRONMENTAL SIMULATION

Only the natural environment, while being used by the actual customer, can really determine the operational reliability of a system. However, there are reasons for environmental simulation.

- It is rare that a specific development project will experience the extremes of the natural environments. For example, there are probabilities that a temperature of or colder than -51 °C will occur when a system will be used, but there is little probability it will occur during a specific open test window. Likewise, temperatures up to and exceeding 49 °C may occur, but again, they may not occur when a specific system is scheduled for testing.

- Natural environments only accelerate or hold an environment during unusual conditions, such as Chinook winds that cause very rapid temperature changes. Environmental chambers can hold temperatures at those levels that can stress or deteriorate circuit boards rapidly. They can cycle the daily temperature and humidity changes as rapid or even faster than what happens during the most unusual weather changes. The example used in this section will illustrate how environmental acceleration can be done several times during a 24-hr period and yet not stress the system beyond what can actually occur during extreme natural conditions. It must be stressed, however, that this test-analyze-and-fix process should not be used to determine if a specific reliability requirement has been achieved. It should be used as a means of quickly finding weaknesses in a design. NASA has no alternative from using environmental simulation, because their the systems are not operationally tested except during an actual missions. Environmental simulation and physics of failure modeling becomes the only means of assuring system reliability.

- Systems being operated by actual users, especially when mounted on platforms such as ground vehicles, planes, and helicopters, require greater expenditures of funds to field test than is required in simulation tests in laboratory environments. Modern laboratory equipment is computer controlled, thereby allowing few man-hours of dedicated technicians, especially when several systems under test (SUT) are operating simultaneously. By tracking failures while environmental simulation is being performed, a growth curve can be generated in the same manner as is done during operational testing.

4. ANALYSIS OF THE ENVIRONMENTS OF USE

A study should be performed to determine where and when the system is to be used. Systems operating on land, sea, and air, such as a global positioning system are subjected to a variety of platform environments. Vibration, acoustic noise, rapid temperature and barometric pressure changes, dust, fungi, salt spray, and poor quality power supply waveforms are likely challenges to the reliability of the system. Each environment is unique as to the failures it precipitates. However, in actuality, an item is challenged by the

interaction of many environments impacting simultaneously, creating a synergy of failure causing mechanisms. Combining accelerated environments should be considered so long as there is congruency with their manner of actual use.[1]

5. RELIABILITY GROWTH WITH ACCELERATED ENVIRONMENTS

Two philosophies of accelerated environmental testing are being advocated. One, which has gone by many names, is currently being called Highly Accelerated Life Testing (HALT). Environments much more stressful than the system will likely experience are used. For example, during HALT, vibration control is expressed in total "G's rms." These units are the integral of the vibration spectrum, which is an over-all value of the vibration being generated. It is not correlated to the spectrum of any specific platform. In addition, temperatures are ramped very rapidly to values higher and lower than would be experienced in any intended environment. The voltages are above and below those specified for the power supplies. The purpose is to have a final design that is very robust at minimum cost of test equipment and time.

A different approach is to determine the environments by measurement and determine those that would most likely cause failures during use. Cycling temperatures as rapidly as would ever be experienced or shake to vibration spectra from actual terrain or flight data will precipitate failures that one could expect in actual use, only faster. As such, these would not be highly accelerated life tests as in the aforementioned paragraph, but they would be Controlled Accelerated Life Testing (CALT). The dimensions of vibration are G^2/Hz and is referred to as the power spectral density (PSD) and is congruent to that of an intended platform. Starting with an actual vibration spectrum and increasing the PDSs a calculated value, the reliability engineer would find relevant product weakness without causing unlikely failure modes. To cause the latter would lead to a redesign of a product that already has long, acceptable life, or a redesign of an item that will not likely fail before it becomes technically obsolete. Financial resources should not be expended on redesigns where they could be better used elsewhere.

On those items where failures can be life threatening, often the best solution is adding active redundancy rather than designing the item to be more reliable. An example is the navigation redundancy required for transoceanic commercial aircraft. Each plane has three navigation systems. Flights are not allowed to leave the terminal unless two of these systems are operational. The risk is too great to attempt long flights with one, and it would not be economical to increase a single system's reliability to where one would be as reliable as two concurrent systems.

Let's look at several environments and the benefits and risks of accelerating them, then look at how they could be combined. The latter is important in that there can be

interaction among the environments that can cause reliability related stresses as well as save test time.[2] They will be presented as two sets of multiple environments which can be combined and accelerated. The first set will be temperature, vibration and voltage cycling and the second set will be humidity and storage temperature cycling.

6. SET #1 - COMBINING THREE TACTICAL ENVIRONMENTS

6.1 Temperature Cycling.

Cyclic temperature stresses, with some exceptions, cause more failures of electronic components than sustained high temperatures. Such failures are caused by the high stresses generated by different coefficients of expansion of the different components, widely varying thermal masses and uneven heat distribution at all levels of assembly. The only reason more temperature cycling related failures do not occur is that the cycling rate is comparatively slow as compared to vibration. The temperature cycling rate results from a combination of factors such as operating vs. non-operating temperatures, platform heating and cooling (heaters and air conditioners), and natural daily temperature cycling from night-to-day and season-to-season. Therefore, the rate of the cycling and the number of additional cycles during a given period of time the normal cycle could occur are the important acceleration factors for these stresses.

Preparation for such testing starts with a temperature survey. The system should have all critical components instrumented to determine the time for the system to reach a steady-state temperature after starting. If the system contains a microprocessor, it should be running a program that exercises its gates, because heat is generated executing a software program. The time it takes each instrumented component to reach steady-state at room temperature and after temperature ramping is important. It will assist during test planning.

Next, the Arrhenius effects need to be taken into account. The life of electronic components decrease exponentially as temperatures increase linearly. Military Standard 810[3] lists the highest ambient temperature as 49 °C, but it remains at that temperature for only approximately 1-hr. The temperature during the day can be expected to remain as high as 48 °C for an additional 3 hr. When the highest operational temperature is coupled with dwell times and internal stabilization times when operating, one can design a test to find the temperature related weaknesses in a system without introducing unlikely failure modes. It also means that dwelling after temperature stabilization may be more important at high temperatures than at the cold temperatures. One could, for example, design a 24-hr test with two high temperature cycles with dwells at least as long as an operational scenario and shorter or no dwells for the two low temperature cycles. This provides the necessary fatigue cycling at both ranges, but the prolonged temperature stresses at only the

high temperatures where Arrhenius related failures are precipitated. In any case, this example allows 4 days of environmentally simulated fatigue stresses each day.

Finally, cold temperatures are mostly related to microprocessors and various mechanical and electromechanical items. Experience has found that some systems will not start during extreme cold conditions. If there is a likelihood that the system is to be cycled off and on during cold weather operations, cold dwells in an non-operational condition should be placed in the test procedures. Because the system would have reached a steady-state condition at shut-off, the time for all thermocoupled components to reach chamber temperature should be fairly short. Once every component is at chamber temperature, the system can be turned on and the chamber temperature can start its climb to room temperature.

Knowing how many full cycles one can perform in a day would be a starting point in estimating the number of days the test may require. If a system is more likely to be used in one environment as compared with the other, the tester takes that into account during the test planning stage.

6.2 Vibration Testing.

Rapid changes are anticipated during the next 5 years in the design of vibration simulation hardware and its associated software. These changes are going to change the methods by which the vibration data is collected, how the power spectral densities (PSDs) are developed for the vibration controllers, and the methods used to accelerate the fatigue in the electronic and electromechnical-mechanical modules of a system. The U.S. Army Harry Diamond Laboratory has a small three axis shaker system (for testing fuzes) and NASA, at the Goddard Space Flight Center, is currently studying a six degree of freedom hydraulic vibration system. The first technical papers of the NASA studies are not expected until the turn of the century. Until then, and probably well through the first decade on the 21st century, the testing community will mostly be evaluating electronic system robustness with single axis shakers. This assumption will guide the content of this section of accelerated vibration testing.

Obtaining the correct vibration environments is the most misunderstood task in performing accelerated testing, especially if the vibration spectra is from MIL STD 810, Environmental Test Methods and Engineering Guidelines[3] or vibration data published in various International Test Operation Procedures. The vibration levels in these publications were developed for the transport certification of high explosive munitions and are several magnitudes higher than the natural vibration environment of the intended platform. The purpose for these amplified spectra is to reduce the risk of a munition exploding while in transit causing extensive loss of human life and property damage. Munition testing in a vibration chamber, located in an impact ammunition area and operating at highly exaggerated vibration spectra, is the only acceptable method allowed for transport certification. When developing electronics for military systems it is recommended that the reliability test

engineer find the correct point-of-contact in Military Standard 810.[3] They are listed for each branch of the Armed Forces. The vibration spectra for each platform is stored in computer files and unpublished test reports that can be retrieved for developing a real time operating environment. When developing electronic systems for nonmilitary platforms (automobiles, trucks, tractors, etc.), each manufacturer has or can obtain the PSD information needed for a CALT program.

Accelerating the vibration environment is a four-fold effort.

- First, one obtains user estimates or historical records of the percentage of time the system is likely to be used in various ground or flight environments.

- Second, vibration data should be collected on all terrains or flight conditions within the expected envelope of use.

- Third, match the likely percentage of use or mission time to each vibration environment. This is important in that studies have found that fatigue life is extended by a factor of 180 when the vibration level is halved. The most conservative method would be to graph all PSD values on log-log coordinates for all terrain or flight conditions for all perspective platforms and envelope all the data points. To decrease the test time, one only has to simulate this worse case envelope of vibration environment(s). Figures 1, 2, and 3 illustrate the envelope of the combined vibration of the harshest vibration spectrum of the HMMWV and the M109 self-propelled howitzer taken from the computer data stored on these two systems at the Aberdeen Test Center. Tables 1,2, and 3 contains the power spectral density (PSD) values of the spectrum.

- Fourth, reduce test time with time compression (TC) by applying an exaggeration factor to the simulated vibration levels. These numbers are placed in the vibration controller and are used as the standard reference during the test. Tables 4, 5, and 6 are the values when TC is applied.

The over all objective of accelerating the laboratory vibration test is to produce the same PSD related damage in the laboratory as the electronic item would receive during a defined period of time during movement. This is done using the assumption that damages accumulates according to Miner's Theory:[4]

$$TC = EF^{3.75}$$
$$EF = (PSD_L/PSD_P)$$

where

TC = Time Compression
EF = Exaggeration Factor
PSD_L = Power Spectral Density to be used during laboratory testing
PSD_P = Power Spectral Density of the platform
3.75 = a constant based upon fatigue of materials

It is recommended that the ratio of the EF not exceed 2.0, because this is an overall estimate and inaccuracies increase as the PSD ratio gets larger. If someone wishes to increase the exaggeration factor to six, one would have to increase the PSD_L thus:

$$TC = (PSD_L/PSD_P)^{3.75}$$
$$TC = 6$$
$$PSD_P = 1$$
$$PSD_L = 6^{(1/3.75)} = 1.61$$

Therefore, multiplying each PSD at each frequency range by 1.61 would increase the fatigue 6-hr of platform hours in 1-hr of laboratory testing. One needs to realize that with a single axis of shaker testing, this has to be repeated three times, once in each axis. Tables 1, 2, and 3 compares the PSD values listed next to the enveloped values of Tables 4, 5, and 6 with the exaggerated values.

One final point needs to be made concerning vibration and its consideration. So far, the discussion concerned the variation of platform vibration amplitude along a frequency range such that it becomes a spectrum for a specific platform for a specific operational environment. Time is a dimension in that spectrum that needs to be addressed. The values in Tables 1, 2, and 3 are the mean values at each frequency. Actually, over every instant of time, the vibration levels vary statistically from several standard deviation smaller than the mean to several standard deviations above the mean. Outliers in both directions are present. As already mentioned , low levels of vibration have minimal effect on fatigue.

Kurtosis justifies using the harshest vibration combinations for vibration simulation, at least for ground vehicles. Extensive vibration studies performed by the vibration test branch at the Aberdeen Test Center have found that wheeled vehicle vibration at any given frequency is not mesokurtic, but platykurtic.[5] (Kurtosis is defined as the fourth moment of the mean and is defined with equations in most statistics text books.) Figure 4 illustrates the three general types of kurtosis, leptokurtic, platykurtic, and mesokurtic.[6] A true mesokurtic distribution of data is Gaussian. The controllers generate random vibration pulses at each frequency band that fits a Gaussian distribution along the vibration spectrum. Because the most stressful vibration pulses occur at the higher vibration levels of each frequency band, and because the platform experiences a greater quantity of higher stresses at

the right tail of the distribution than the controller generates, there is justification in extending the time of the of the TC values beyond what would be indicated in the mission profile. For example, the mission profile would normally indicate that the harshest vibration enveloped for the vibration simulation would only occur 25% of the time, but to be conservative, one may want to apply this vibration level 50% of the time. One can be certain that the right extremes of a platykurtic distribution contains a greater quantity of damaging vibration than the right extremes of a mesokurtic distribution. (When testing munitions, compensation for kurtosis is handled by doubling the values in the spectrum before applying Miner's Theory. Experience with electronics life testing has shown these vibration levels to be so harsh that parts which had very little likelihood of failing in actual applications, were failing during laboratory simulation.)[2] If and when the test engineers can insert the kurtosis values into their controllers along with the PSDs and frequencies, then all exaggeration processes should be re-examined.

6.3 Voltage Testing.

The power supplies in any electronic system needs to be exercised to the extremes of the voltages variances it is expected to meet. If it is expected to be used in only a single range of alternate current (ac) voltages and a predetermined number of phases, the problem of evaluating the system is not too difficult. The voltages need to be varied only to the maximum extremes they have normally experienced. However, if the system is mobile, the electricity may be supplied via an inverter, an automotive alternator or a portable generator. In addition, ac power supplies may not have a true sinusoidal wave form and the direct current (dc) power supply may contain ripples. There has been major improvements in the quality of power sources in recent years, but one should be aware of the sources of available power for the SUT available and their characteristics. Environmental simulation needs to duplicate or use the actual power supply the SUT will have in actual use.

7. COMBINING ENVIRONMENTS

There is no single recommended method of combining simulated environments. However, one should use some logical methodology to relate the use environment to the temperature survey. Although it is not necessary, it helps the testers to fit environmental cycles into a 24-hr block. Also, one needs to define an ambient temperature for the purpose of setting a baseline temperature (such as 20 °C), a high chamber temperature (such as 49 °C), and a low chamber temperature (such as -51 °C). Unless there is a need to use temperature shock, electrical heaters and cascaded refrigeration units should elevate and decrease chamber temperature changes as fast as 4 °C/ min. If mechanical refrigeration can meet the temperature ramping requirements, then it should be used. It causes the air to reach dew points, which in itself does not make it a humidity chamber, but it does provide an extra, but uncontrolled, environmental stress. If not, either liquid carbon dioxide or liquid nitrogen

is capable of inducing very rapid temperature reduction, but at the expense of driving out all water vapor.

7.1 An Example.

As this example progresses through a combined test design one should refer to Figure 5. Assume that

• the maximum rate the intended platform would likely change temperatures (either heating or cooling during extreme conditions) is 1 °/min; and

• the temperature survey found that

- the internal stabilization of the SUT following ramping to the hottest chamber temperature of 49 °C, occurs in 40 min

- the internal stabilization following drop to room temperature occurs in 60 min (it takes longer for the temperature to stabilize going down, because the SUT is generating heat)

- the internal stabilization following ramping to the coldest temperature of -51 °C occurs in 90 min

- the internal stabilization when the SUT is totally shut down at -54 °C is 60 min

- the temperature of stabilization at ambient following climbing from -54 °C is 50 min

• from studying the tactical operational temperatures

- the hot temperature dwell should be at least 3 hr

- the cold temperature dwell following stabilization, is not of primary concern.

7.2 Temperature Cycling.

Figure 5 illustrates how during a 24-hr period, temperature simulation of 4 days use in the most severe environments may be planned. This has been accomplished (never subjecting the SUT to temperatures exceeding what it would likely experience in actual use), yet dwelling longer at the highest temperatures that would likely occur during

actual use. Likewise, the rate of temperature change (though high) does not exceed the likely highest it could possibly experience on a ground platform.

7.3 Vibration Axis Change.

Changing the axis of a shaker is time consuming and labor intensive. Usually, a 5-day repetition of the 24-hr schedule, with a break over the weekend to save on excessive technician overtime pay, leaves an hour or so on a Saturday morning for a performance test, followed by a change to the shaker orientation. On Monday mornings, before 8:00 a.m. start of testing, the SUT performance is rechecked.

7.4 Vibration PSD Levels.

Communication and chemical agent detection systems are examples of items that are activated at the start of an armed conflict and are shut down only for repairs and succession of hostilities. The platforms, on which these systems are mounted, move in accordance with the mission. For this example, assume a dynamic situation where vehicles are moving over 25% during any 120-hr period. However, taking into account the platykurtic distribution of ground platforms, the time for vibration will be doubled to 50% to compensate for the actual right tail vibration levels the controllers can not duplicate. If one were to devise a test where the orientation of the shaker would be changed once a week (on a Saturday for example), and the testing would be performed in 3-week clusters, one would have to design the vibration for each axis to simulate a total of 720 hr in a 120-hr time period. This means that for every hour of temperature testing, the system needs to experience 6-hr period of vibration testing. As discussed in the Miner's Theory section, a six-fold increase is obtained by multiplying the PSD levels found in Tables 1, 2, and 3 by 1.61. Tables 4, 5, and 6 would be the vibration levels used in this example. The vibration on time is shown in Figure 5 below the temperature profiles. The vibration is only shut down for when the SUT is shut down for a cold temperature dwell and the short times for daily performance testing.

7.5 Voltages.

The voltages should be varied through the ranges of the power supply. If it is assumed that the system is being powered by a ground vehicle alternator, a voltage low of 20 Vdc will be the lowest, a nominal of 24 Vdc and a highest of 30 Vdc. Because systems are occasionally shut down for very short periods of time for cleaning, filter changes and cold stabilization, such power shut-offs are also placed in the test plan. Such shut downs cause additional stresses on the circuits and by allowing them to reoccur, they test the robustness of the system.[7]

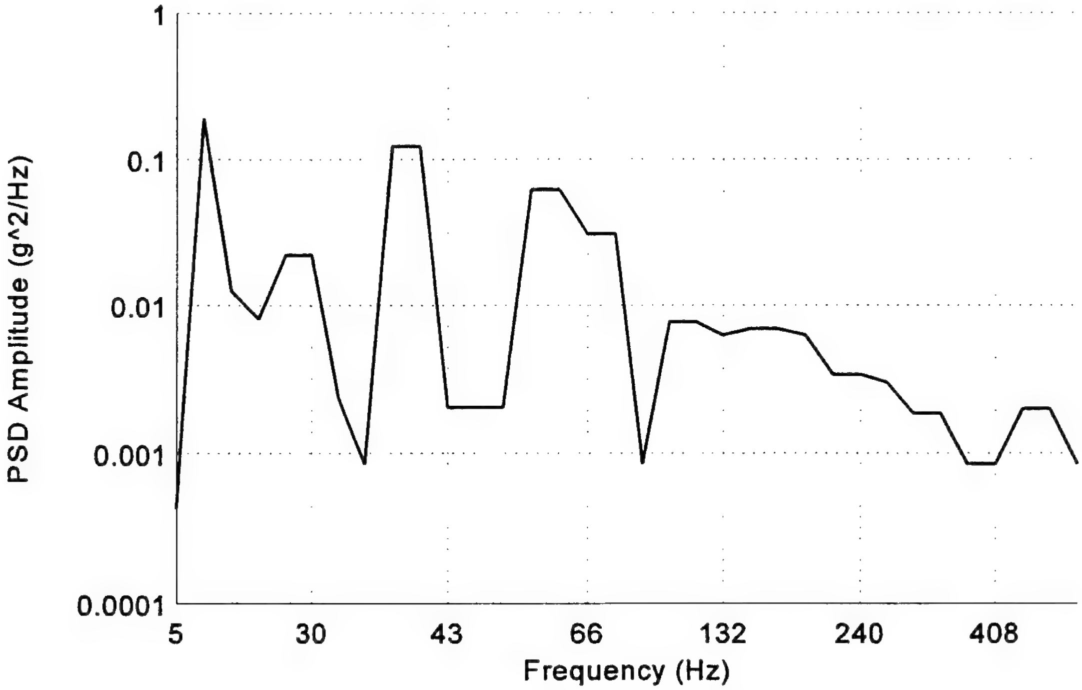
8. SET#2 - STORAGE TESTING

Storage testing at the extremes of hot and cold is necessary for items that are in their tactical state and not in their shipping packages. If thermal imaging is available, it would certainly be helpful in this test, because a hard failure may not occur, but molecular migration may have started and could possibly be detected with this instrumentation. Such testing may be run on the same materiel previously used in the combined environmental testing.

Storage cycling, using the induced temperatures as recommended in MIL STD 810, is suitable as stated for this work. If cycling starts on a Monday and continues for 2 weeks, sufficient time should be accumulated to find any detrimental effects. The testing series should start with hot storage, as it most likely will be the less stressful of the two. After the system has been checked for failures and degradation, the materiel can be placed into cold storage. Such testing should be done with mechanical refrigeration to produce a dew point. Because the system is not operated during storage testing, no heat is generated to drive the moisture out. The moisture will freeze and the expansion and contraction during the freeze-thaw process will place stresses on the system.

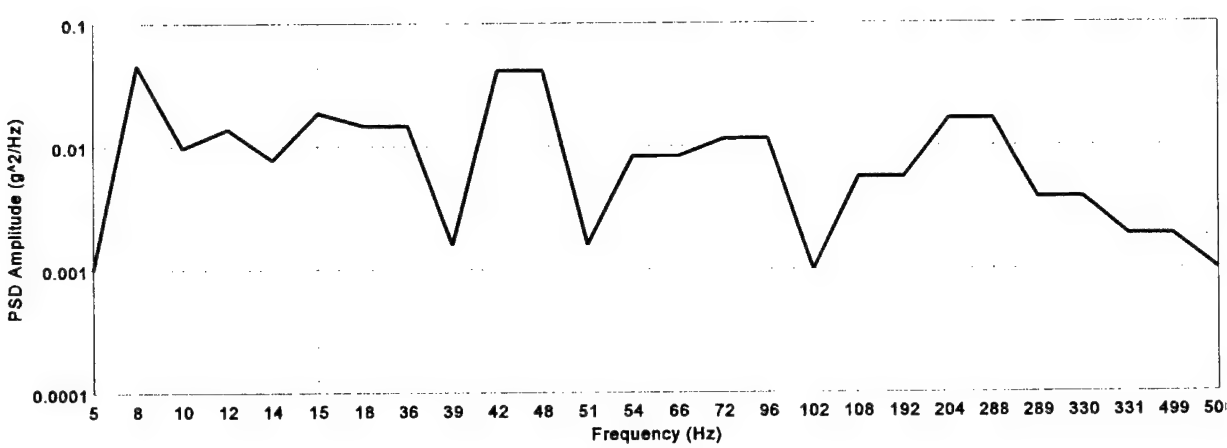
9. OTHER COMBINED TESTING

Military Standard 810 contains several environmental tests that can be simulated in a laboratory for reliability purposes. Fungus, humidity, salt fog, solar radiation, and sand and dust tests are among others mentioned in MIL STD 810. One has to weigh the cost effectiveness of simulation versus the natural environment in test planning. First, there is no reasonable way some acceleration factor can be determined from such testing. Second, the time spent in a chamber may be about the same as would be required in a natural environment. Finally, nature automatically combines tropic environments at a particular time and location with great repeatability. The hot, humid environments of Panama can find corrosion problems, many kinds of fungus (more than a chamber can offer), bacteria and salt fog. In addition, the laboratories in Panama are well equipped to analyze these problems and make redesign recommendations. The same logic can be used for desert and arctic conditions. Wind, blowing snow at severely cold temperatures, or dust at severely hot temperatures will find weaknesses in a product that environmental chambers can not duplicate, especially the man-machine interface. The synergy of using both are required to build reliability into a product.



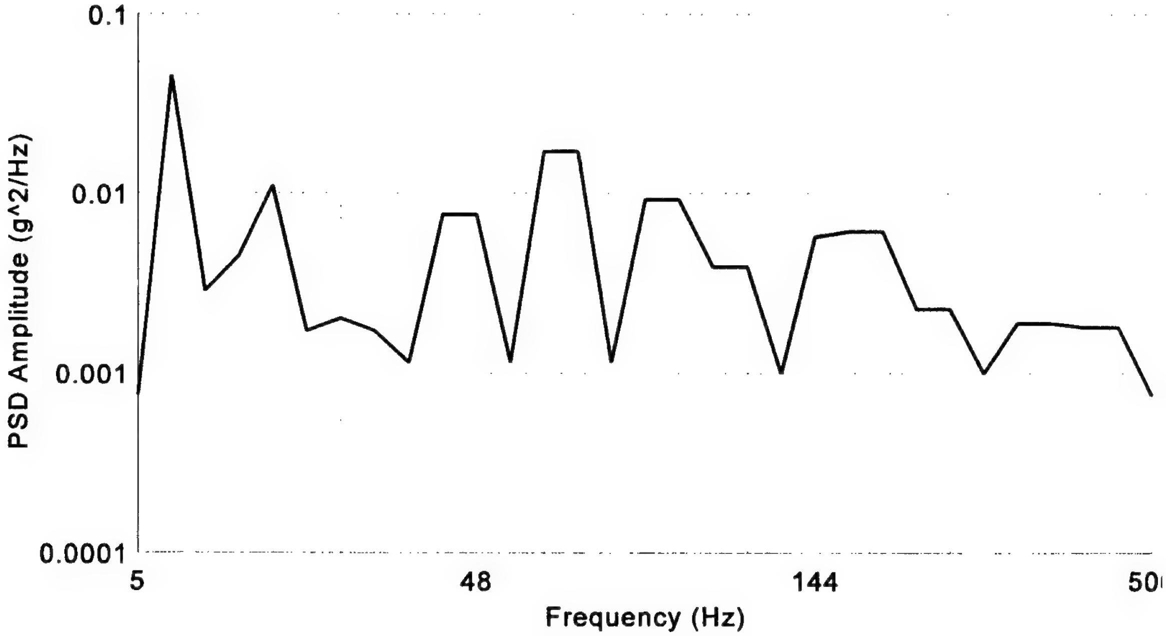
(One hour of vibration equals one hour of operation)

Figure 1. Envelope of HMMWV and M109 Power Spectral Density - Vertical Axis



(One hour of vibration equals one hour of operation)

Figure 2. Envelope of HMMWV and M109 Power Spectral Density - Transverse Axis



(One hour of vibration equals one hour of operation)

Figure 3. Envelope of HMMWV and M109 Power Spectral Density - Longitudinal Axis

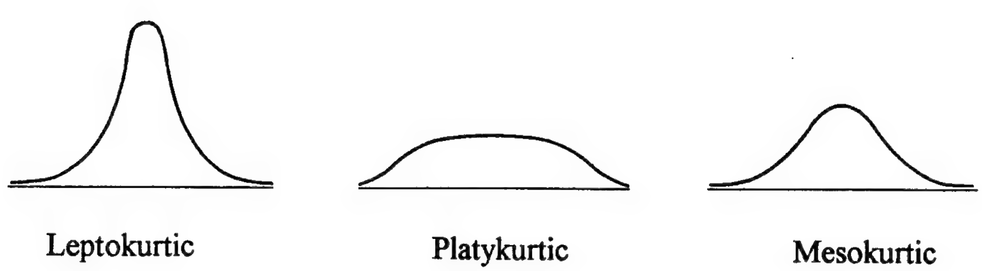
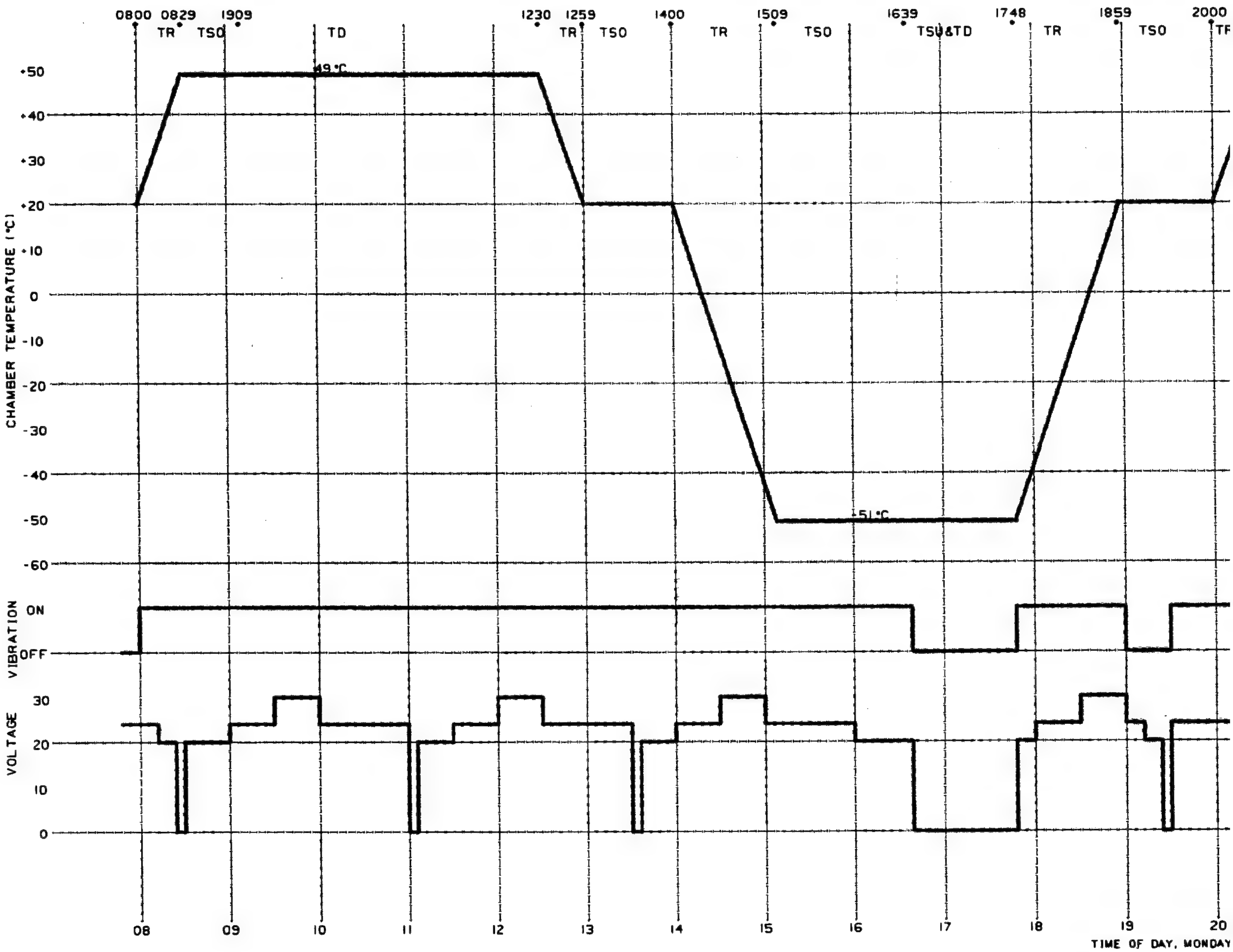


Figure 4. Three Types of Kurtosis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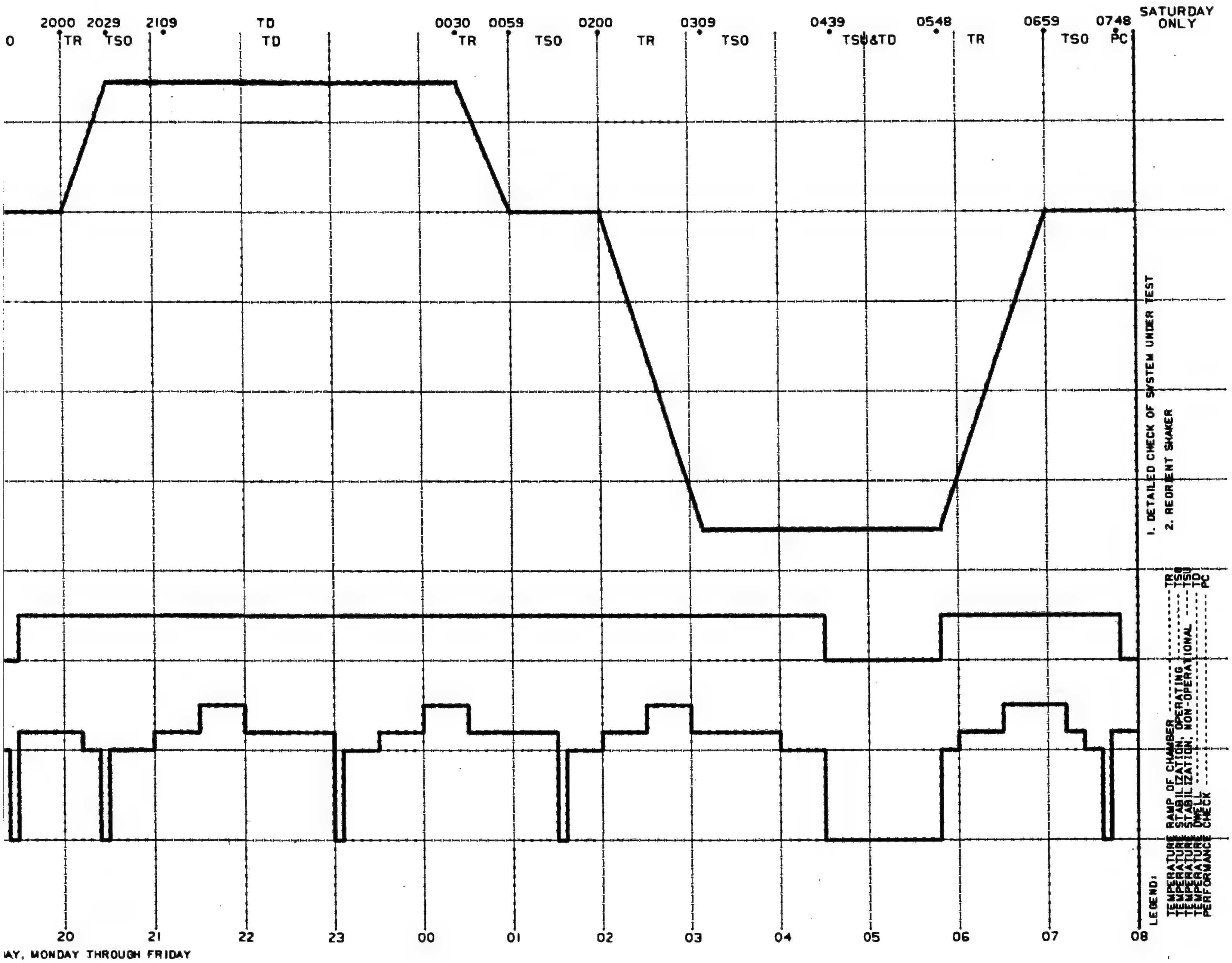

Figure 5. Combined Operational Environmental Stress Schedule

Table 1. Breakpoints of the Envelope of HMMWV and M109 Power Spectral Density - Vertical Axis (1 hr of Vibration Equals 1 hr of Operation)

Breakpoints							
Freq	PSD Value	Freq	PSD Value	Freq	PSD Value	Freq	PSD Value
5	.00043	42	.12285	102	.00768	253	.00185
8	.19031	43	.00203	126	.00768	288	.00185
11	.01268	48	.00203	132	.00623	289	.00085
16	.00811	49	.06168	144	.00688	408	.00085
18	.02205	60	.06168	168	.00688	409	.00198
30	.02205	63	.00085	192	.00623	499	.00198
32	.00240	66	.03068	193	.00338	500	.00085
34	.00085	96	.03068	240	.00338		
36	.12285	97	.00085	252	.00300		

Table 2. Breakpoints of the Envelope of HMMWV and M109 Power Spectral Density - Transverse Axis (1 hr of Vibration Equals 1 hr of Operation)

Breakpoints							
Freq	PSD Value	Freq	PSD Value	Freq	PSD Value	Freq	PSD Value
5	.00100	36	.01463	72	.01143	289	.00380
8	.04549	39	.00160	96	.01143	330	.00380
10	.00975	42	.04098	102	.00100	331	.00190
12	.01380	48	.04098	108	.00558	499	.00190
14	.00779	51	.00160	192	.00558	500	.00100
15	.01859	54	.00830	204	.01650		
18	.01463	66	.00830	288	.01650		

Table 3. Breakpoints of the Envelope of HMMWV and M109 Power Spectral Density - Longitudinal Axis (1 hr of Vibration Equals 6 hr of Operation)

Breakpoints							
Freq	PSD Value	Freq	PSD Value	Freq	PSD Value	Freq	PSD Value
5	.00075	39	.00115	90	.00923	252	.00228
8	.04549	42	.00763	96	.00393	270	.00100
11	.00289	48	.00763	126	.00393	288	.00190
13	.00451	51	.00115	135	.00100	378	.00190
16	.01104	54	.01698	144	.00573	379	.00180
19	.00173	66	.01698	168	.00615	499	.00180
24	.00203	69	.00115	192	.00615	500	.00075
36	.00173	72	.00923	193			

Table 4. Breakpoints of the Envelope of HMMWV and M109 Power Spectral Density - Vertical Axis (1 hr of Vibration Equals 6 hr of Operation)

Breakpoints							
Freq	PSD Value	Freq	PSD Value	Freq	PSD Value	Freq	PSD Value
5	.00069	42	.19779	102	.01236	253	.00298
8	.30640	43	.00327	126	.01236	288	.00298
11	.02041	48	.00327	132	.01003	289	.00136
16	.01306	49	.09930	144	.01108	408	.00136
18	.03550	60	.09930	168	.01108	409	.00319
30	.03550	63	.00136	192	.01003	499	.00319
32	.00386	66	.04939	193	.00544	500	.00136
34	.00136	96	.04939	240	.00544		
36	.19779	97	.00136	252	.00483		

Table 5. Breakpoints of the Envelope of HMMWV and M109 Power Spectral Density - Transverse Axis (1 hr of Vibration Equals 6 hr of Operation)

Breakpoints							
Freq	PSD Value	Freq	PSD Value	Freq	PSD Value	Freq	PSD Value
5	.00161	36	.02355	72	.01840	289	.00612
8	.07323	39	.00258	96	.01840	330	.00612
10	.01569	42	.06598	102	.00161	331	.00306
12	.02222	48	.06598	108	.00898	499	.00306
14	.01254	51	.00258	192	.00898	500	.00161
15	.02993	54	.01336	204	.02656		
18	.02355	66	.01336	288	.02656		

Table 6. Breakpoint of the Envelope of HMMWV AND M109 Power Spectral Density - Longitudinal Axis (1 hr of Vibration Equals 6 hr of Operation)

Breakpoints							
Freq	PSD Value	Freq	PSD Value	Freq	PSD Value	Freq	PSD Value
5	.00121	39	.00185	90	.01486	252	.00367
8	.07324	42	.01228	96	.00633	270	.00161
11	.00465	48	.01228	126	.00633	288	.00306
13	.00726	51	.00185	135	.00161	378	.00306
16	.01777	54	.02734	144	.00922	379	.00290
19	.00279	66	.02734	168	.00990	499	.00290
24	.00327	69	.00185	192	.00990	500	.00121
36	.00279	72	.01486	193			

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